How Linacs Work

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Neutrino Factory and Muon Collider Collaboration Mtg.
Jan. 20, 2006

People

- Experiments in Fermilab Muon Test Area (MTA)
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  - A. Moretti, A. Bross, Z. Qian FNAL
  - Y. Torun, IIT
  - D. Li, M. Zisman, LBL
  - R. Rimmer, JLab
- Modeling
  - Z. Insepov, A. Hassanein, I. Konkashbaev, ANL
- Surface studies at Northwestern
  - D. Seidman, J. Sebastian, K. Yoon NW
  - P. Bauer, FNAL

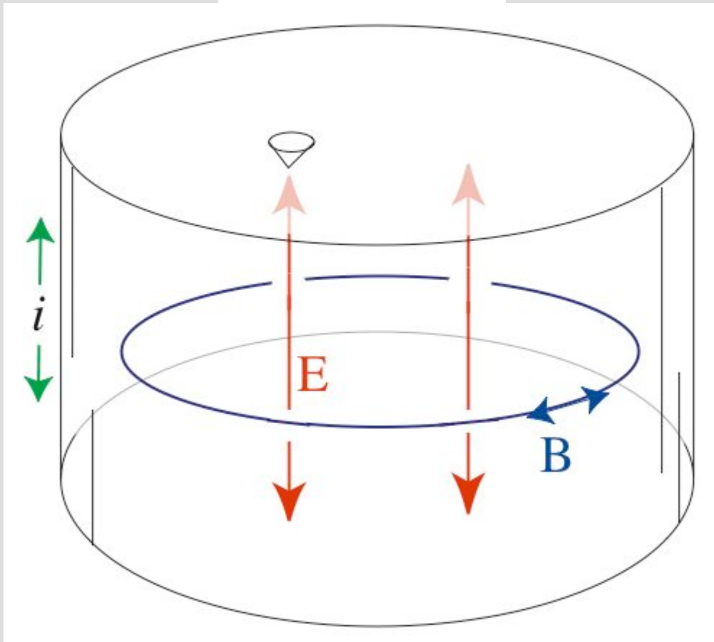
How Linacs fail.

Normal metals

- Stresses from electric fields exceed material tensile strength.
  $E \sim 7$ GV/m

Superconductors*

- Field emission heats cavity before tensile stress limit.
  $E \sim 4$ GV/m



Normal metals

- Skin currents damage walls.
  $\Delta T \sim 100^0$

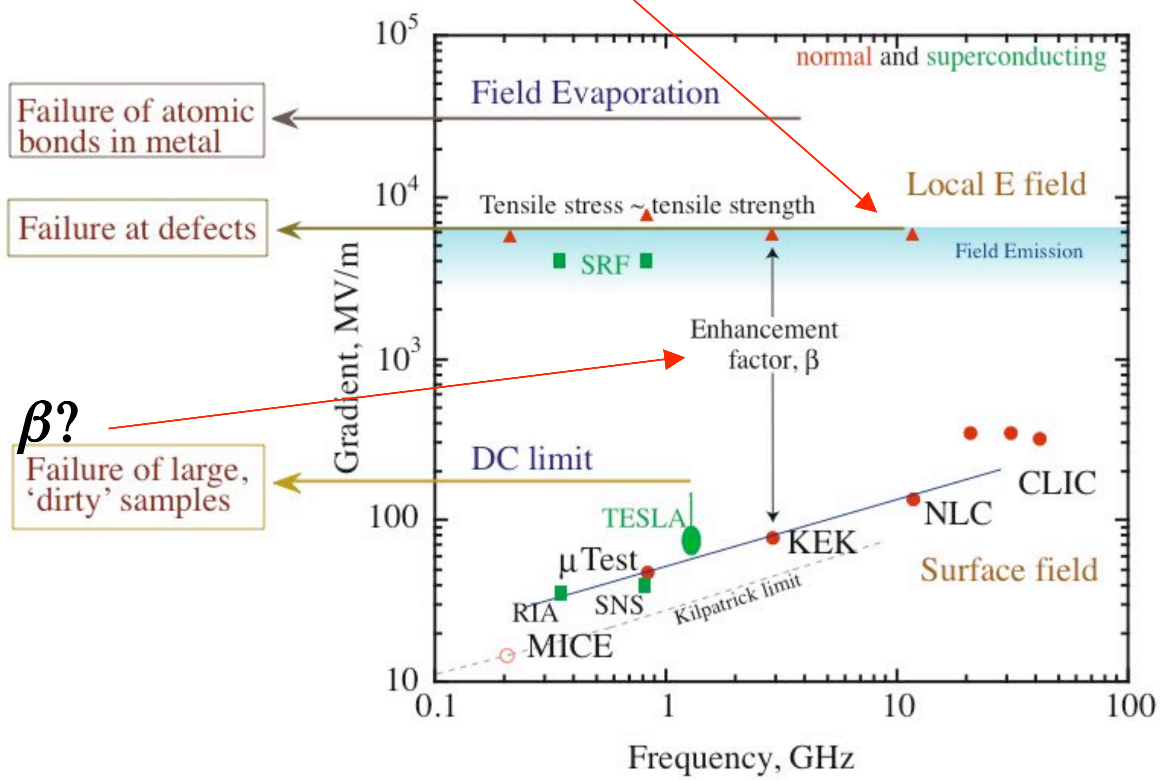
Superconductors

- $B > H_{c1}$, material goes normal
  $B \sim 180$ mT

The Problem

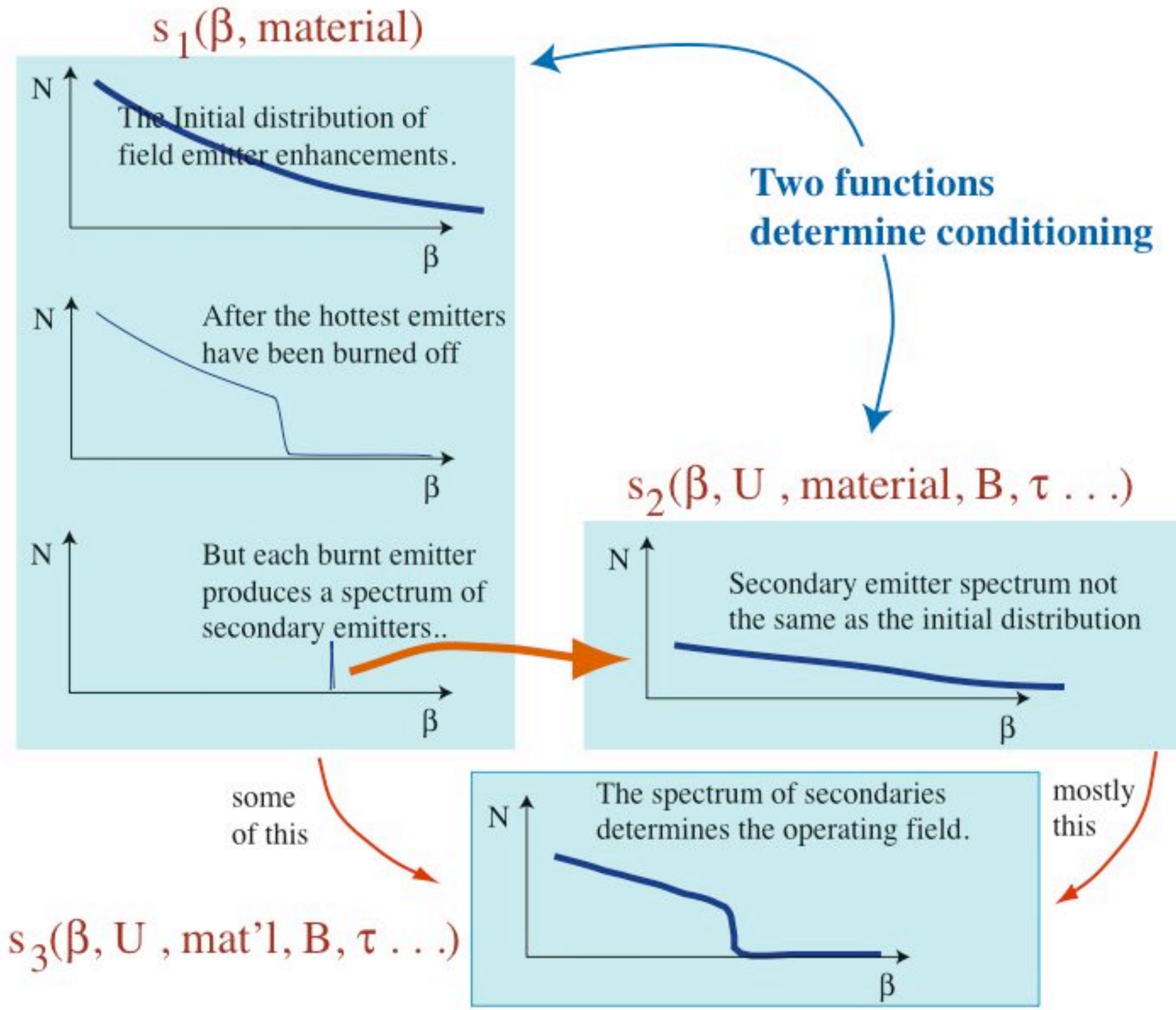
- We want be able to calculate the maximum field any cavity can reach - not so much because we want to know this number, but because we want to know what factors determine the maximum field, to design better cavities.

- We can understand failures at high local fields.



- **But, what determines β?**
  ($\beta = E_{local}/E_{surf}$)

The Solution: damage determines everything



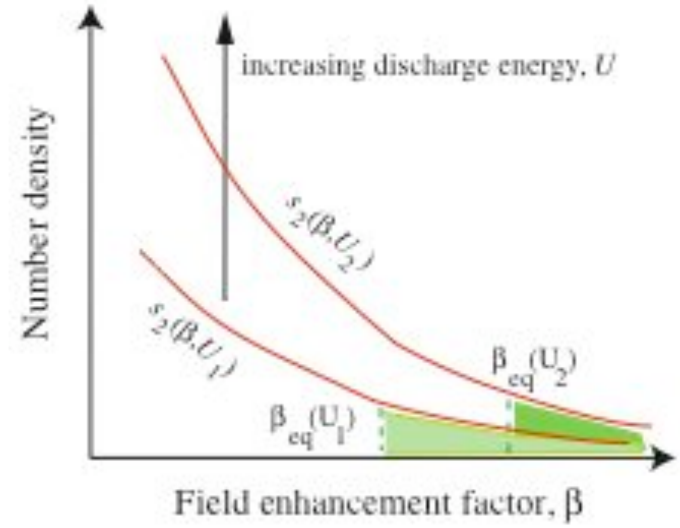
We can calculate β_{eq} from our measurements of $s_2(\beta)$.

- Any event shouldn't make a more active site.

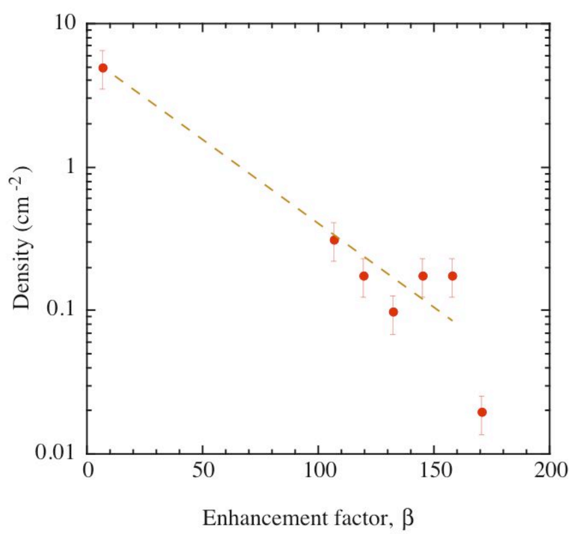
$$\int_{\beta_{eq}}^{\infty} s_2(\beta)d\beta = 1$$

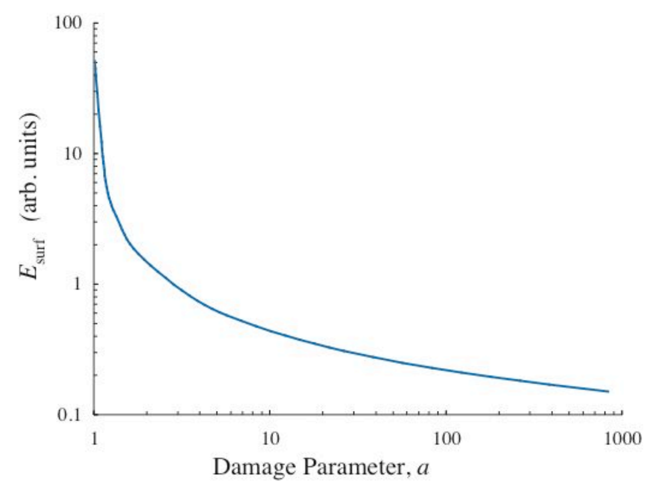
assume $s_2(\beta) \sim a \exp(-b\beta)$

then $\beta_{eq} \approx -\ln(b/a)/b$



giving $E_{surf} = \dfrac{E_{local}}{\beta} \approx -\dfrac{\sqrt{2T/\varepsilon_0}}{\ln(b/a)/b}$



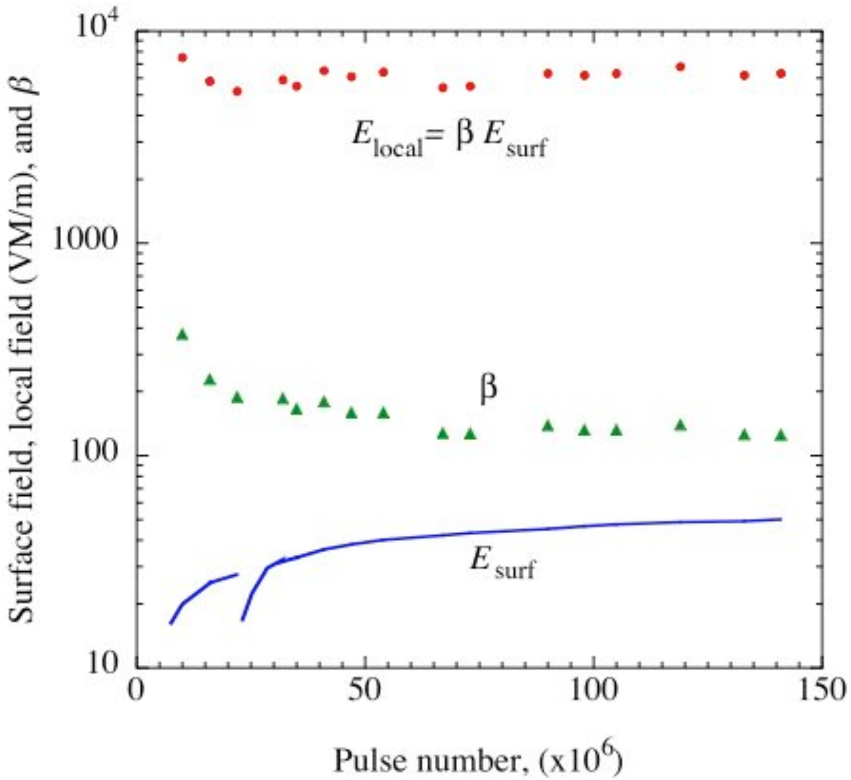


in all linac data.

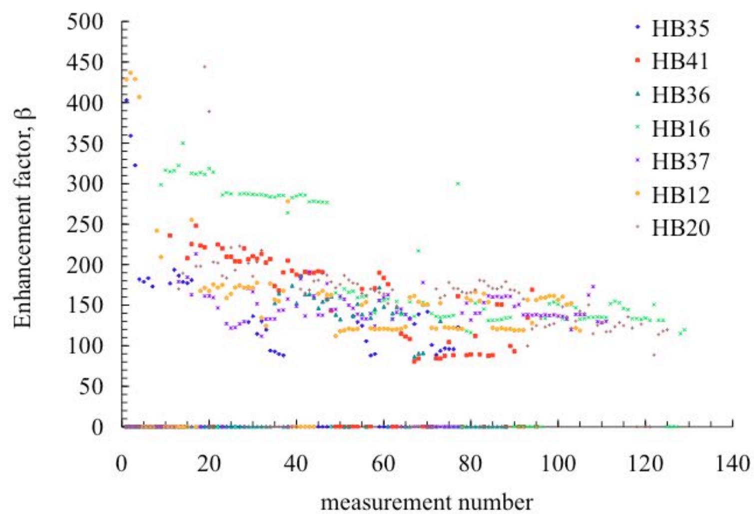
Using the model: I) Conditioning

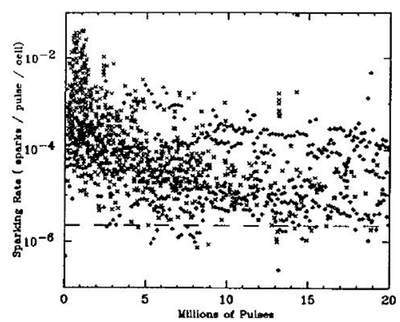
- Only the emitters change, everything else constant.
- The best data on this is from conditioning the KEK S-band linac
- Superconducting cavities also condition. SNS vs. Fermilab linac

KEK



SNS

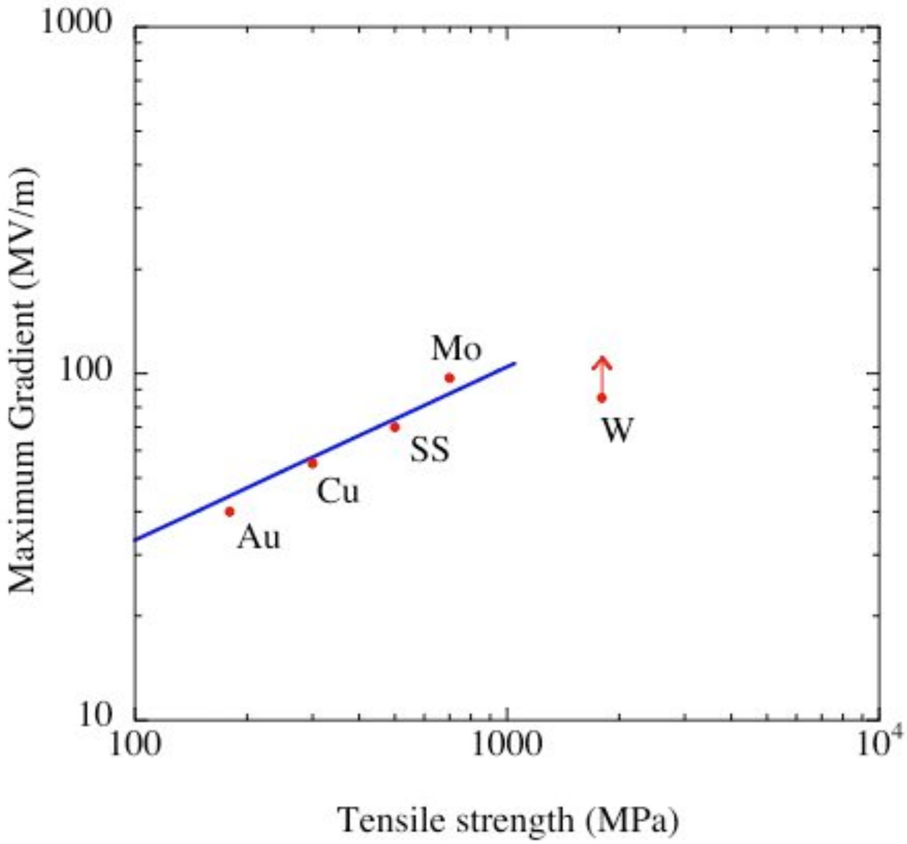




FNAL/linac

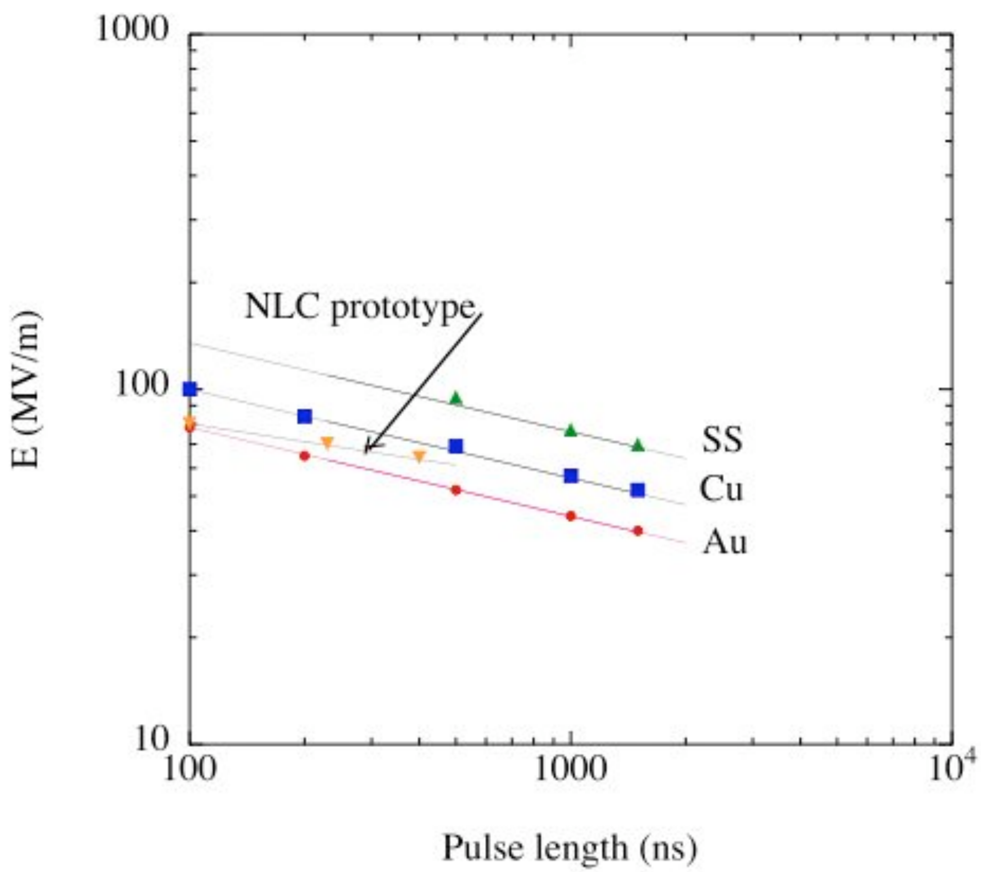
Using the model: II) Materials

- Only materials change, everything else constant.
- The model argues that tensile strength is the dominant effect.
- $E_{surf} = \frac{E_{local}}{\beta} \approx -\frac{\sqrt{2T/\varepsilon_0}}{\ln(b/a)/b}$



Using the model: III) Pulse length

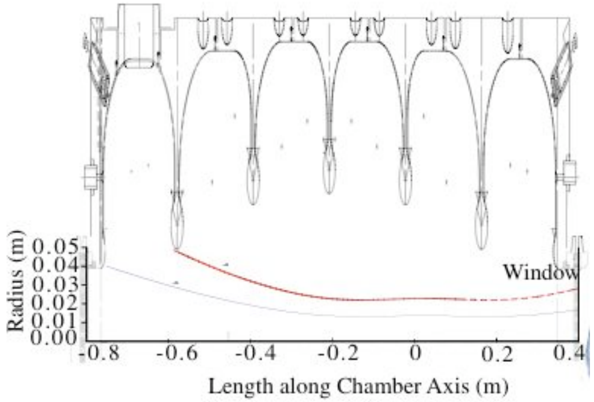
- Only pulse length changes, everything else constant.
- More damage ➜ lower gradients
- Predictions and data show no dependence on position of breakdown within pulse.

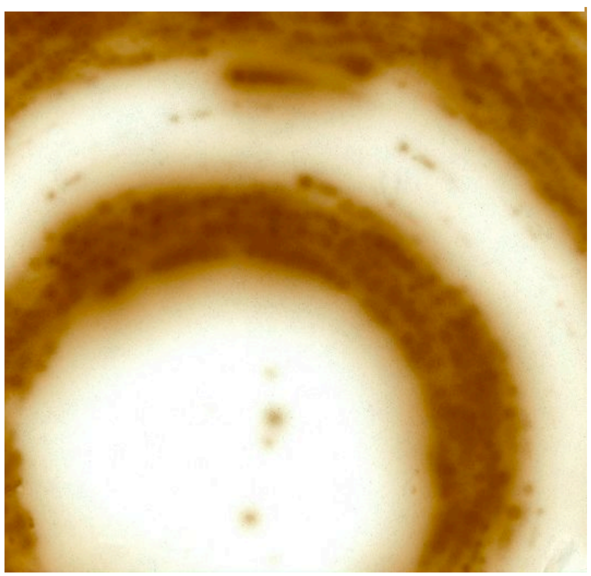


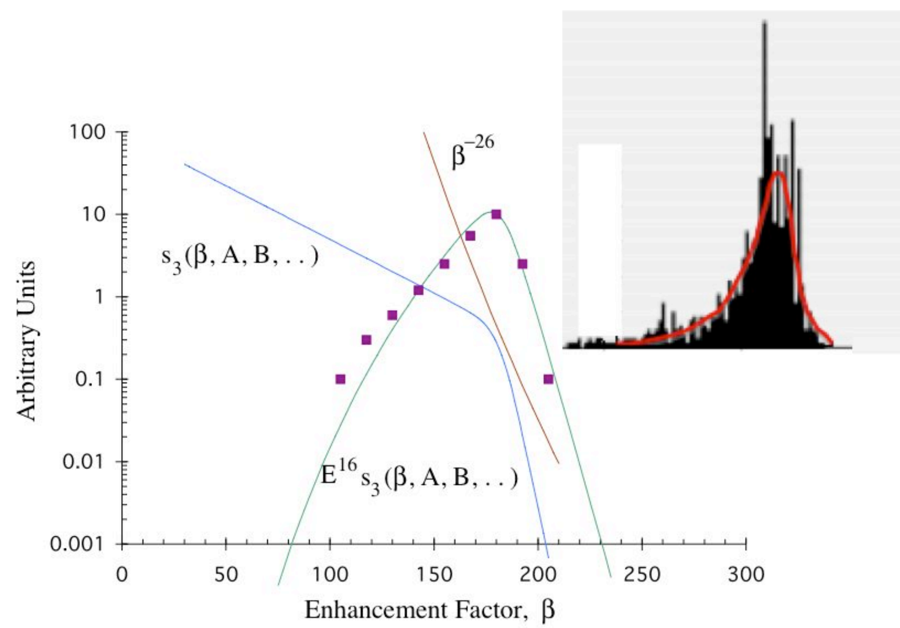
Using the model: IV) The fully-conditioned state

- When you look at emitters, they are all the same strength.
- Assume $s_3(\beta) = s_2(\beta)/(e^{(\beta-\beta_{eq})/c}+1)$ (F-D cutoff - very sharp β^{-25})

- Images of emitters . .. . show emitter strengths
  optical densitometer shows cutoff
  (weighted by field emission $I=E^n$)

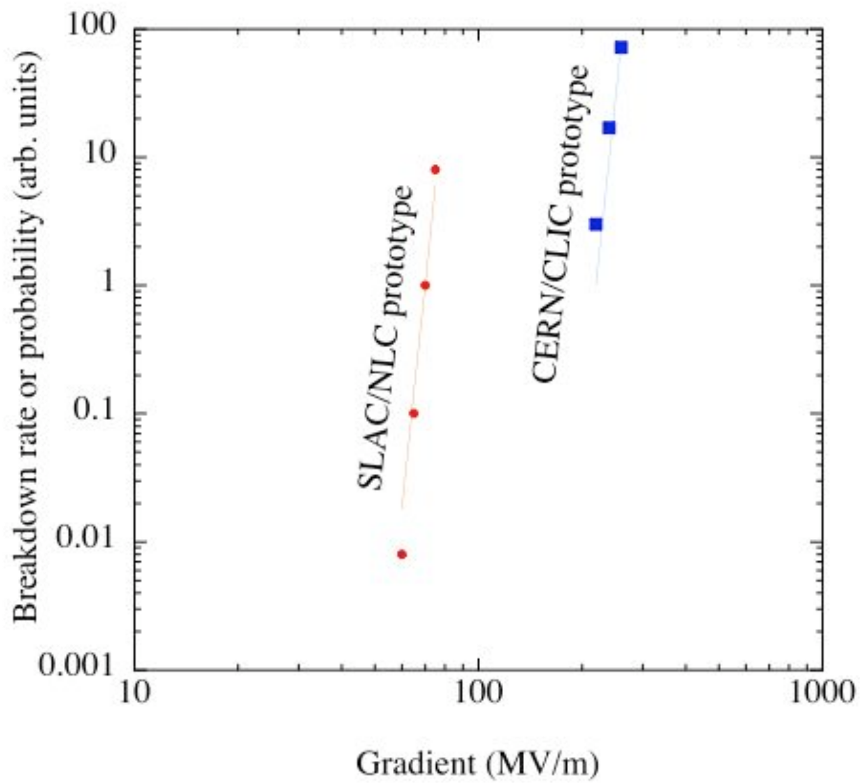






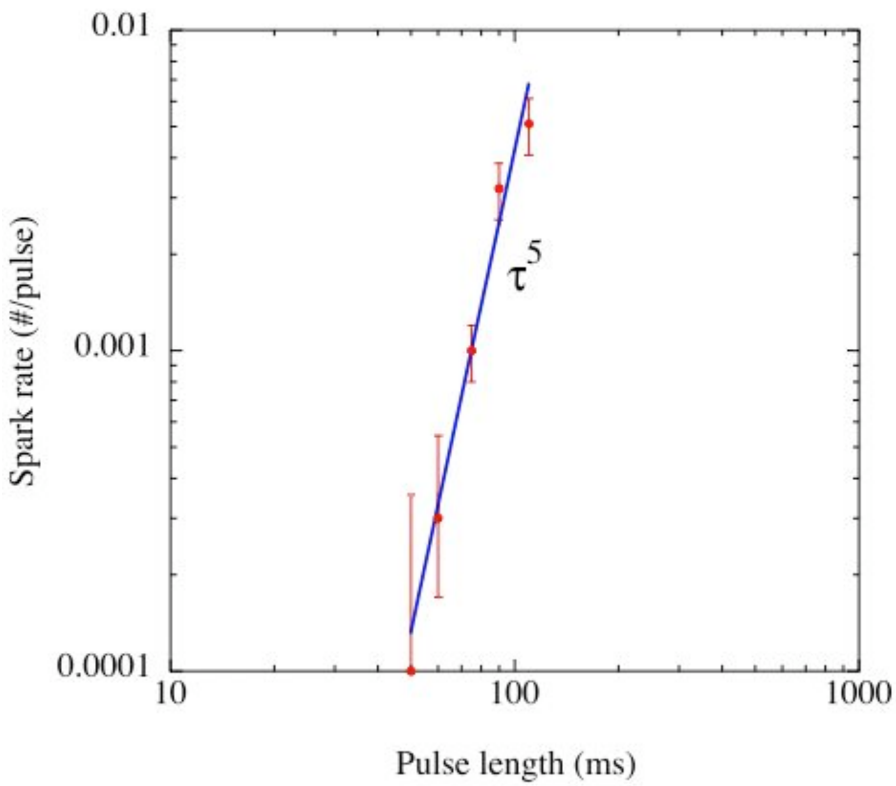
Using the model: V) Breakdown rates vs. *E*.

- These are surprisingly sharp, yet consistent with fully-conditioned state
- Thresholds go like $\sim E^{25}$.



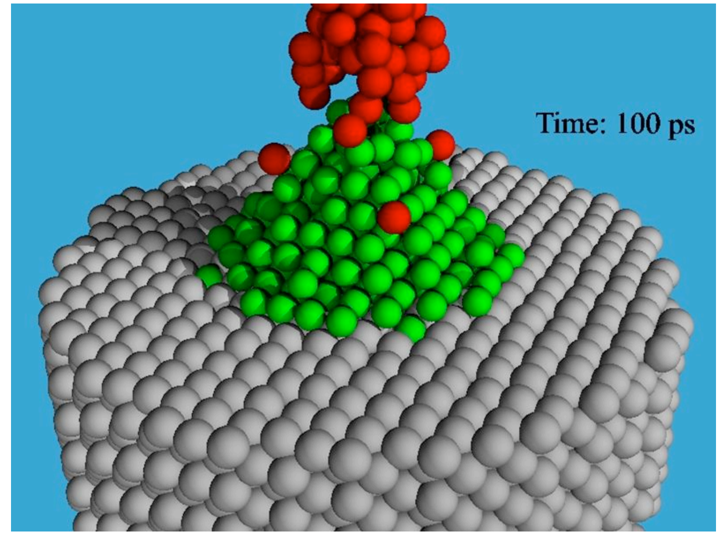
Using the model: VI) Breakdown rates vs. pulse length

- Data from the Fermilab Linac conditioning.



Using the model: VII) Temperature dependence

- A molecular dynamics model predicts little temperature dependence. (Insepov)
- This is consistent with CERN/CLIC results.



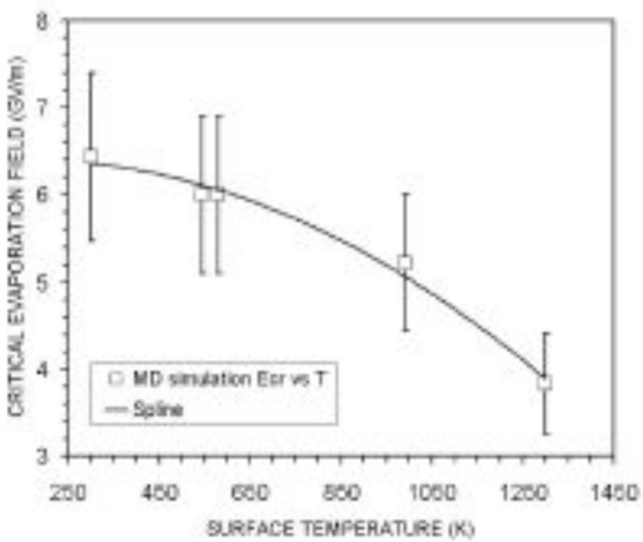


FIG. 2. Observed temperature dependence of critical evaporation field for removing cluster of ~ 200 Cu ions.

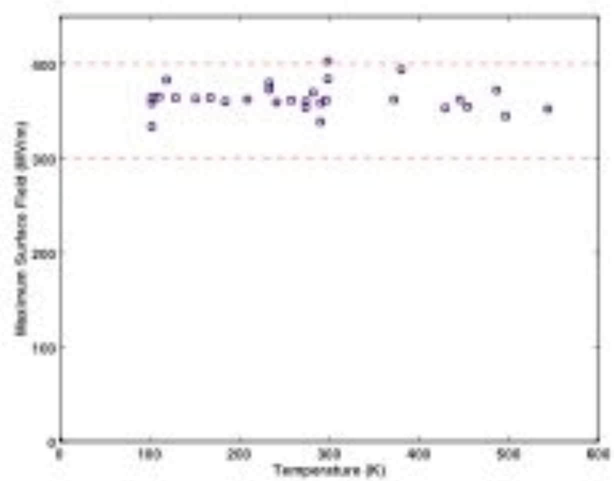
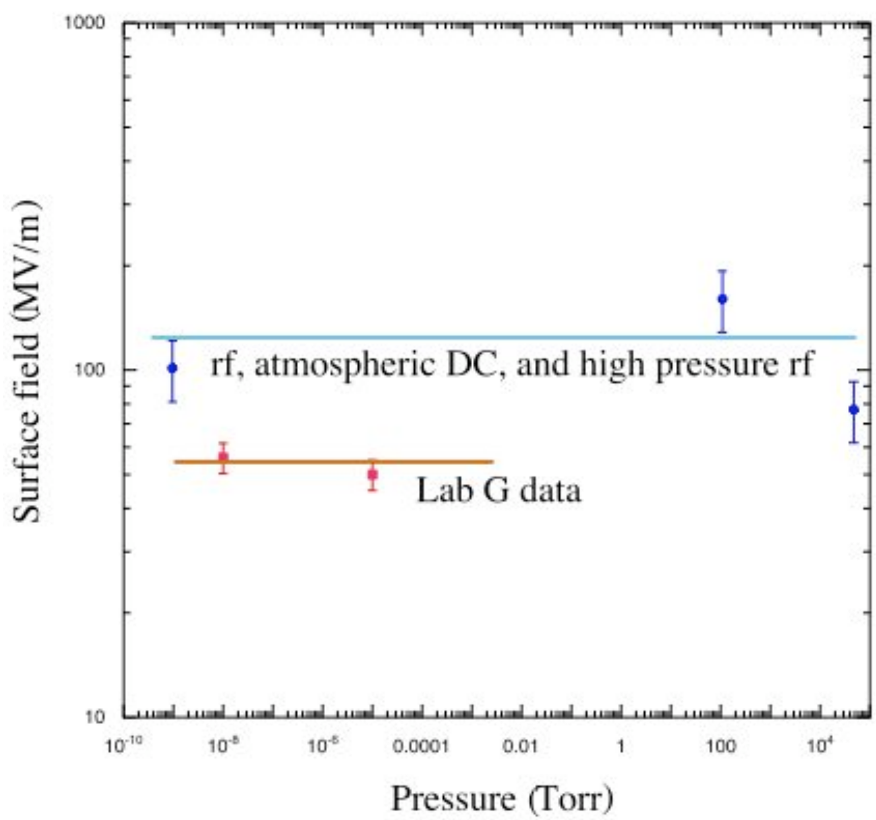


FIG. 6 (color online). Temperature dependence of maximum surface field.

Using the model: X) Gas Pressure and type

- Our model argues that gas pressure is not relevant for H_2 and N_2.
- Data confirms this over >15 orders of magnitude in pressure.
- We can also explain how SF_6 can affect breakdown.

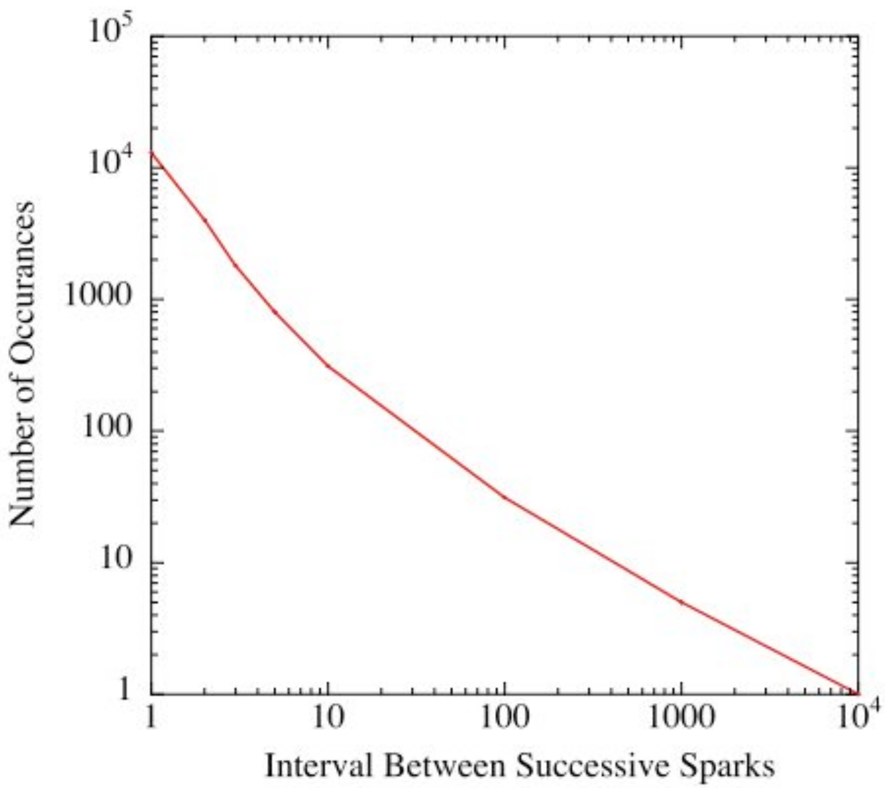


Muons Inc (Johnson et al) have new data.

Using the model: VIII) Spitfests

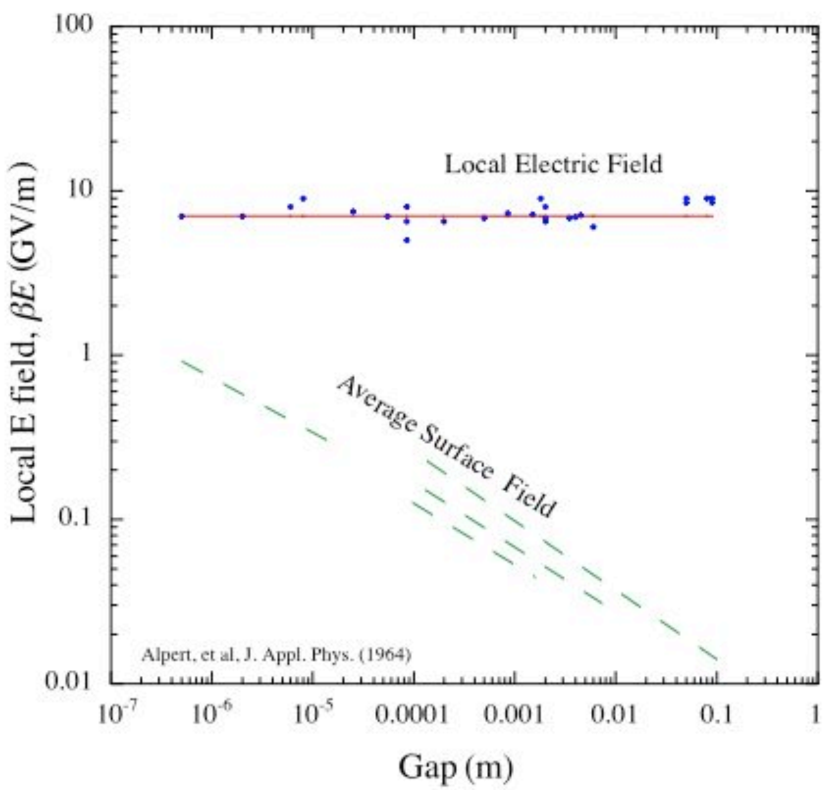
- SLAC named the phenomenon, but early Fermilab data is better.

- The primary cause of breakdown events is damage left by the last event.



Using the model: X) DC breakdown

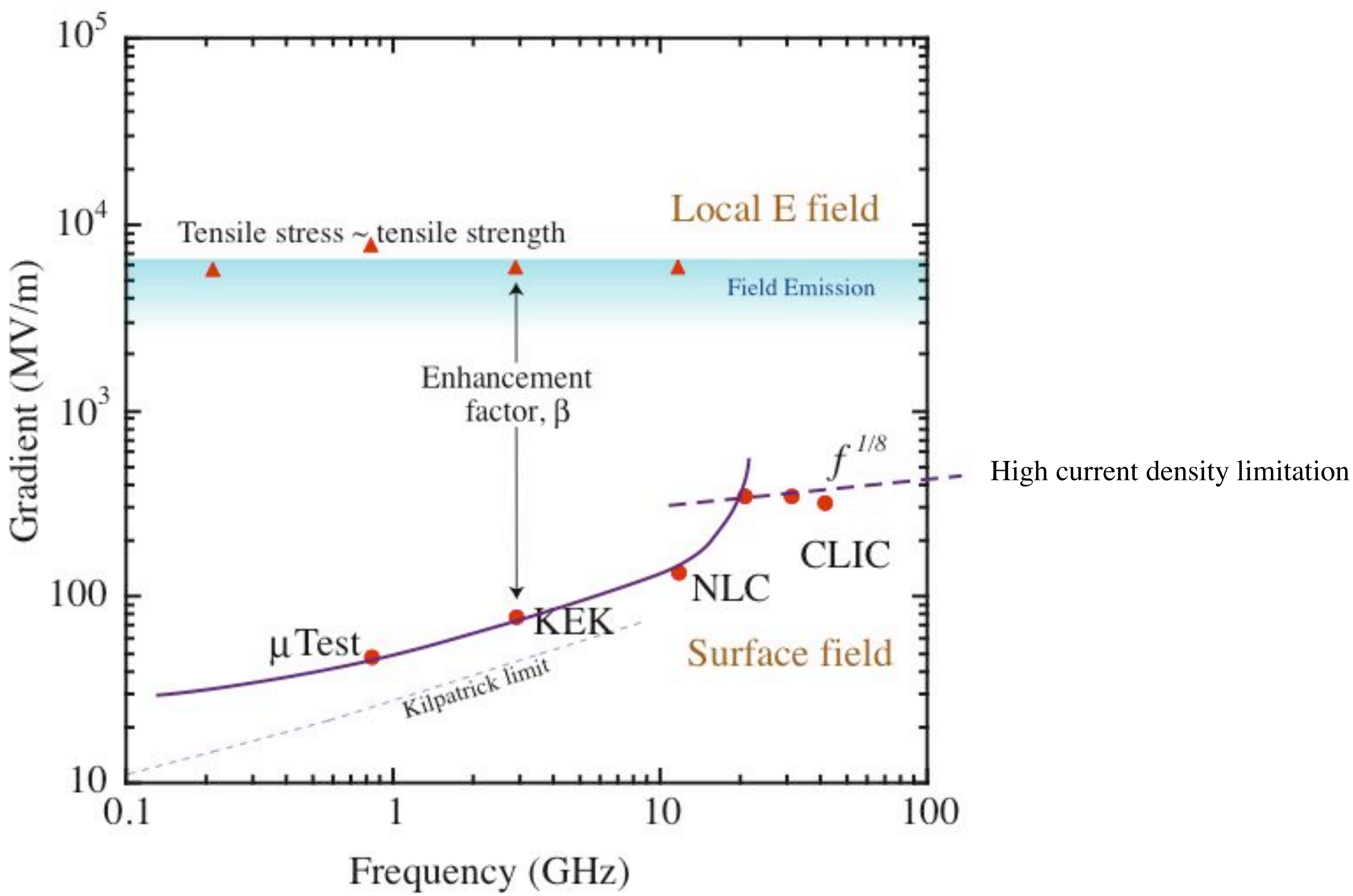
- This also fits the model, with breakdown at 7 GV/m.
- Most of this data is very old and unreliable, but they did clever things.
- Vacuum and cleaning techniques were not always well done.



Using the model: XI) Maximum field vs. frequency

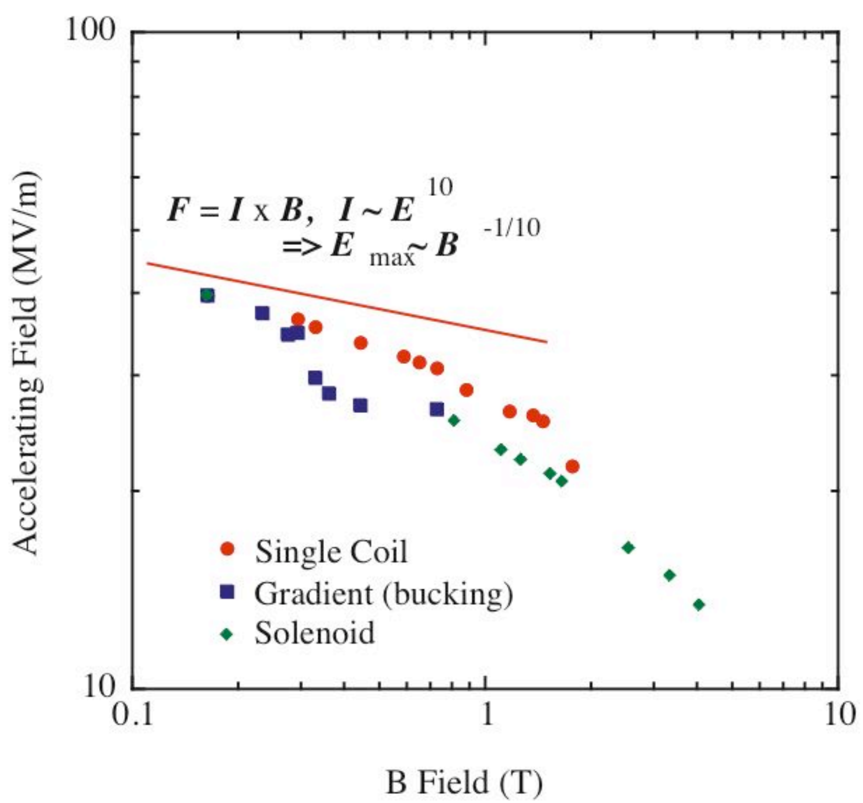
- Each cavity / PS system is unique.

- Our model gives Kilpatrick-like scaling laws.



Using the model: XII) High Solenoidal fields

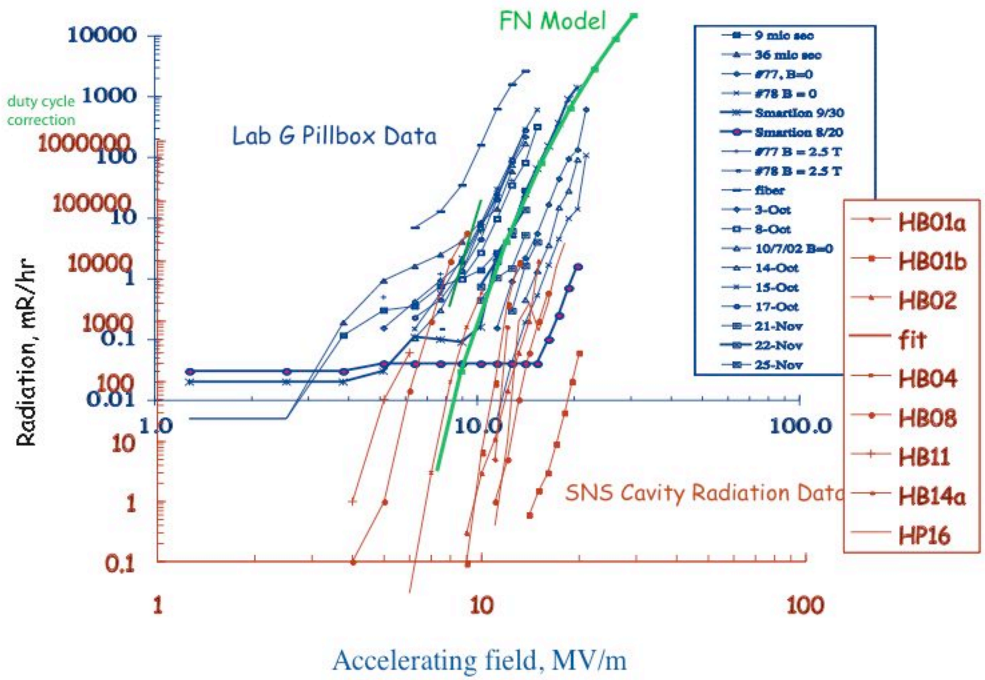
- This behavior is consistent with mechanical stress causing breakdown
- Preliminary data may not be precise at high fields,
- Contributions from other effects are possible.

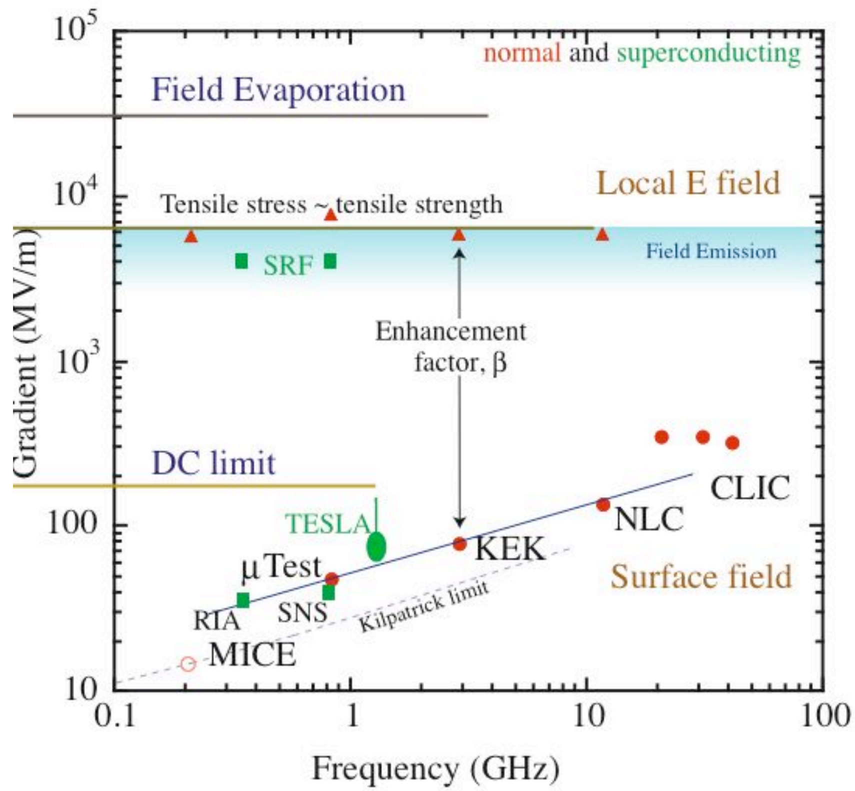


Using the model: XIII) Superconducing rf

- For SCRF Emax = (4 GV/m)/ β, NCRF Emax = (7 GV/m)/ β

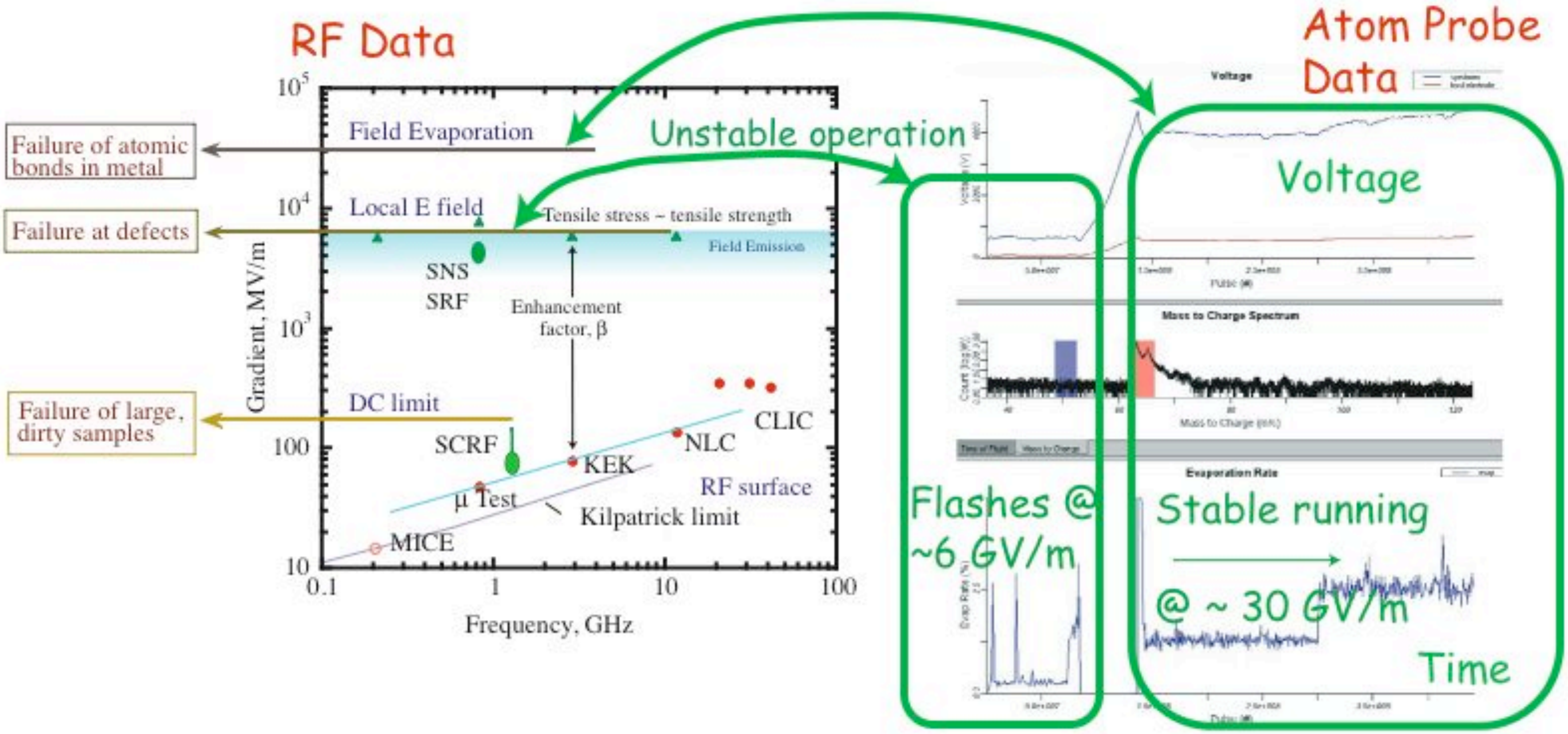
- Radiation levels, show SCRF for SNS has similar problems to NCRF.





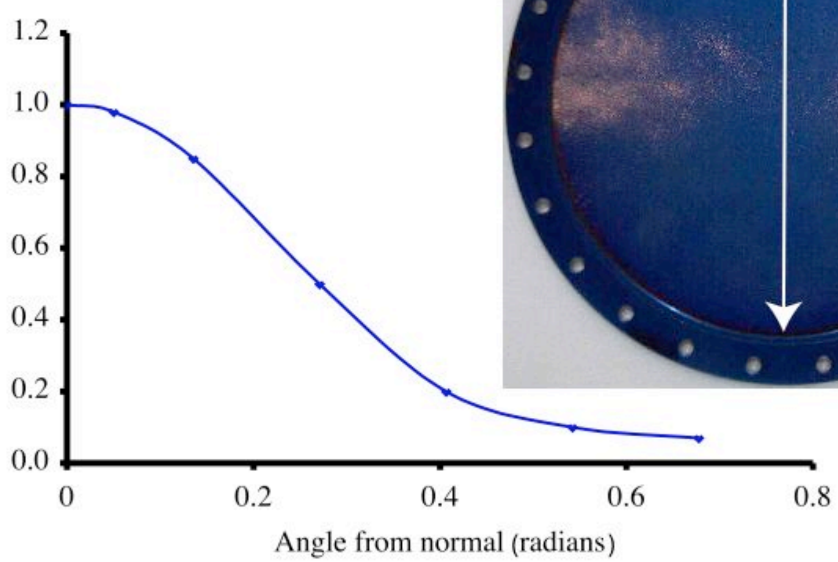
Using the model: XIV) Atom Probe Measurements

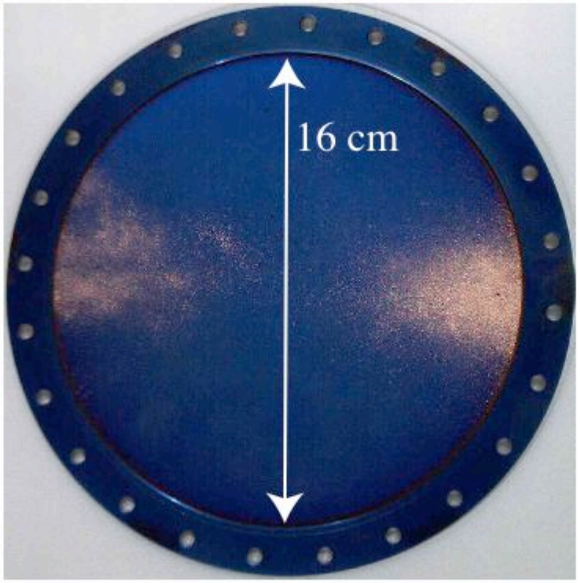
- Atom probe measurements show sample failure at approximately 7 GV/m.



Using the model: XV) Extending the model, geometry etc.

- Cavity shape seems to affect the maximum field.
- Cavity shape also affects the distribution of damage.
- There should be a correlation. Unfinished business.





Ways to improve and test this model

Modeling

Need to be able to factor out individual effects, (power, geometry etc.).
Why is the cutoff so sharp?
What about fatigue? Plasma spots? Resistive heating?

rf measurements, lab expts We need better data.

SLAC: mat'l tests in waveguide breakdown
Fermilab Linac: pulse length, breakdown rate, spitfest mesurements
Fermilab MTA: mat'l tests, 805 & 201 MHz tests, Be tests
Jlab: meas. of $s_1(\beta)$, $s_2(\beta)$, $s_3(\beta)$ on field emission microscope, mat'l tests
Epion Corp. Modification of damage spectra

Atom Probe Tomography

Systematic studies of different metals and oxides are needed

High currents in materials

No work ever done to look at this mechanism

Conclusions

- This new model can explain **all** the data - and suggest improvements.
- Superconducting improvements
  Learn how to make layered superconductors, (material science).
- Normal conducting improvements
  A variety of methods can be used to control damage in cavities
  Understand materials effects.
  A number of loose ends need to be cleared up